Elliptic Flow Fluctuations at RHIC and more

Paul Sorensen
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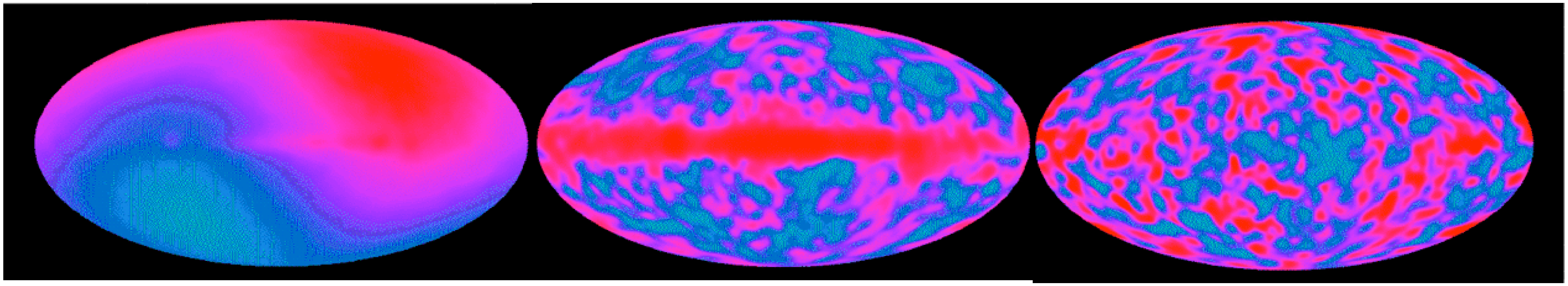

and more = super-horizon fluctuations and fluctuations in the initial conditions

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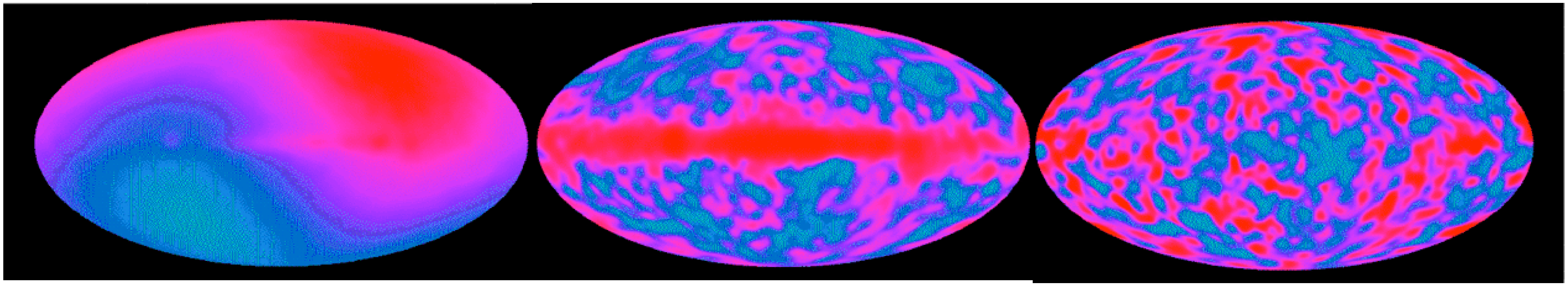
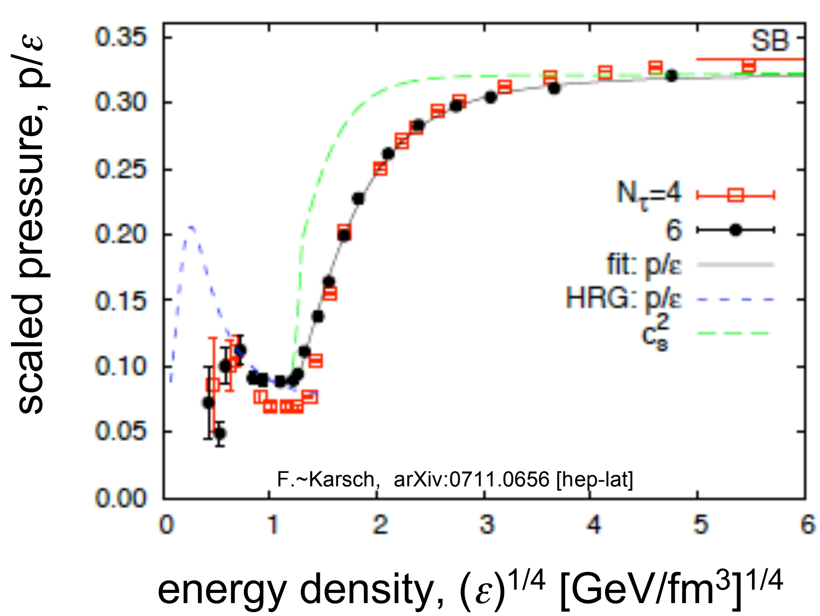
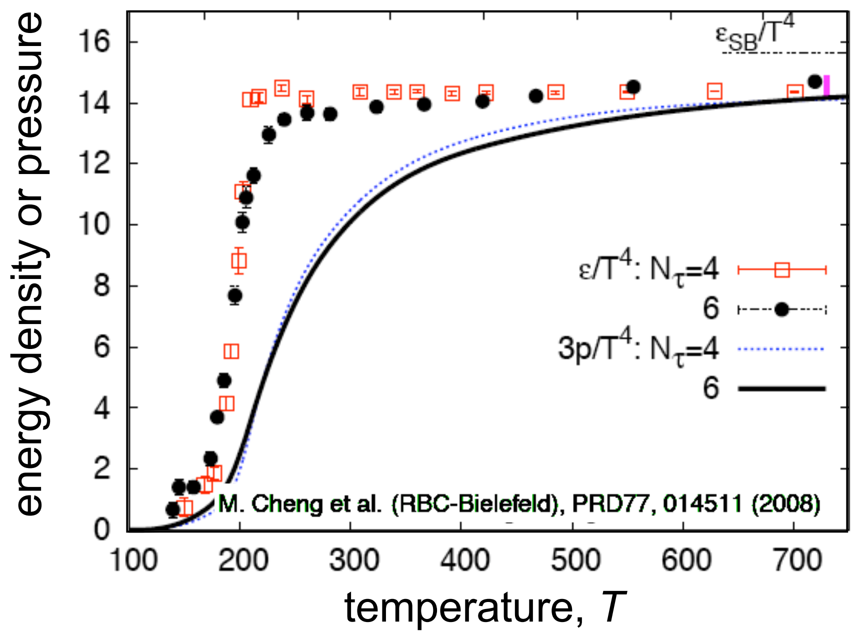


QGP in theory

Quark Gluon Plasma established theoretically

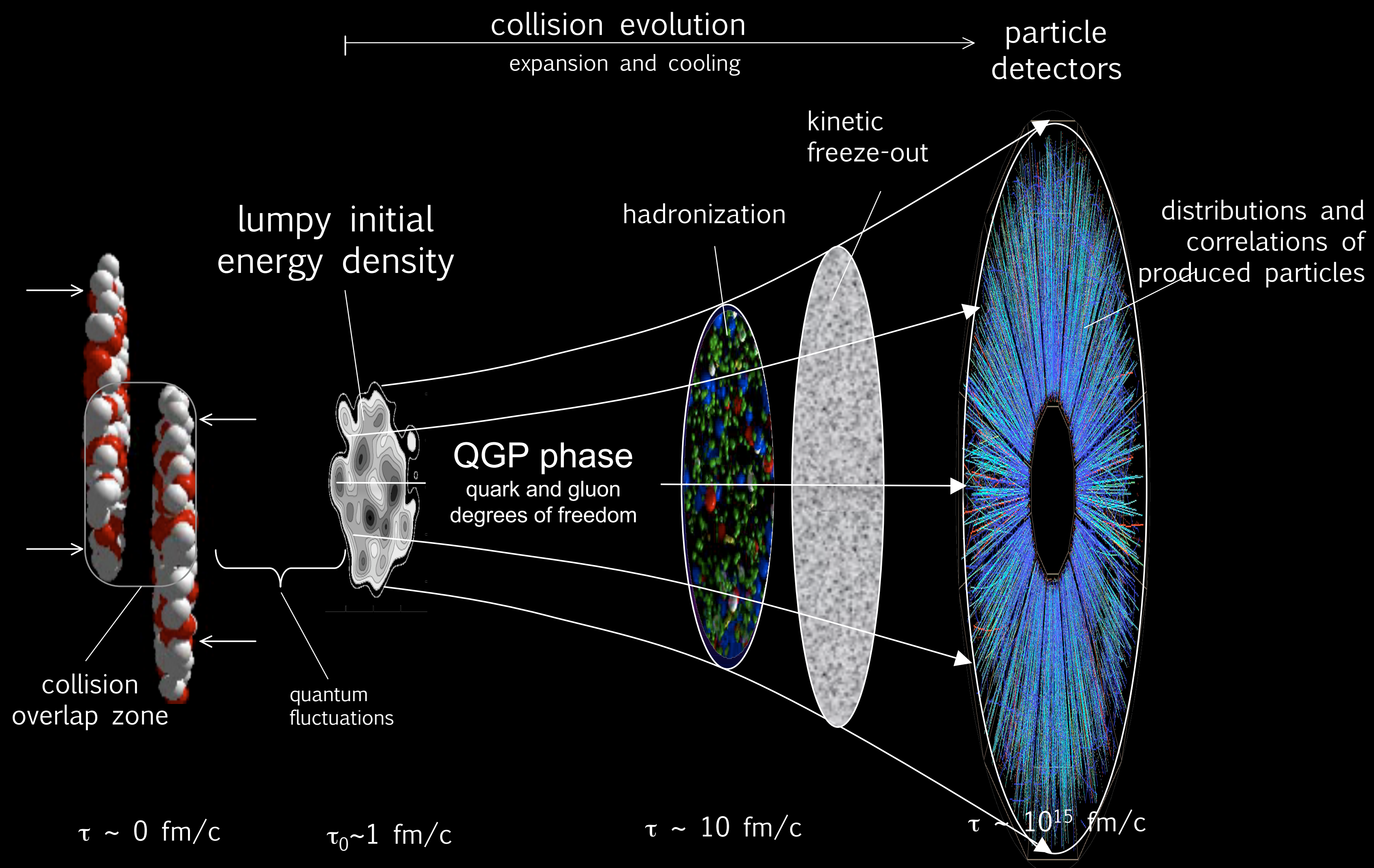
Lattice calculations indicate a rapid crossover accompanied by an increase in the number of degrees of freedom





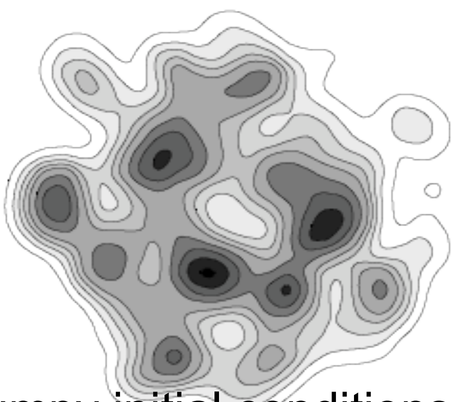
How can QGP be studied in the lab?

Nuclear collisions and the QGP expansion

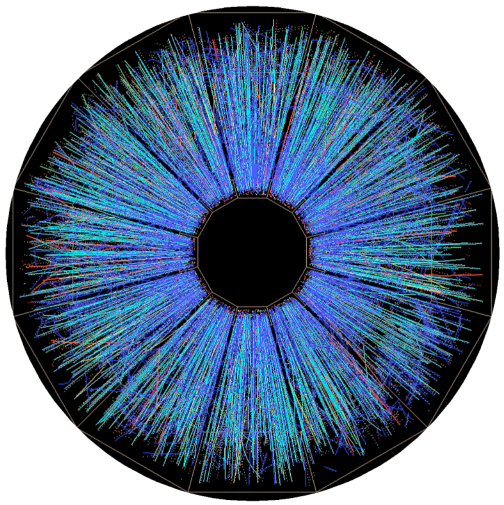


Correlations and Fluctuations

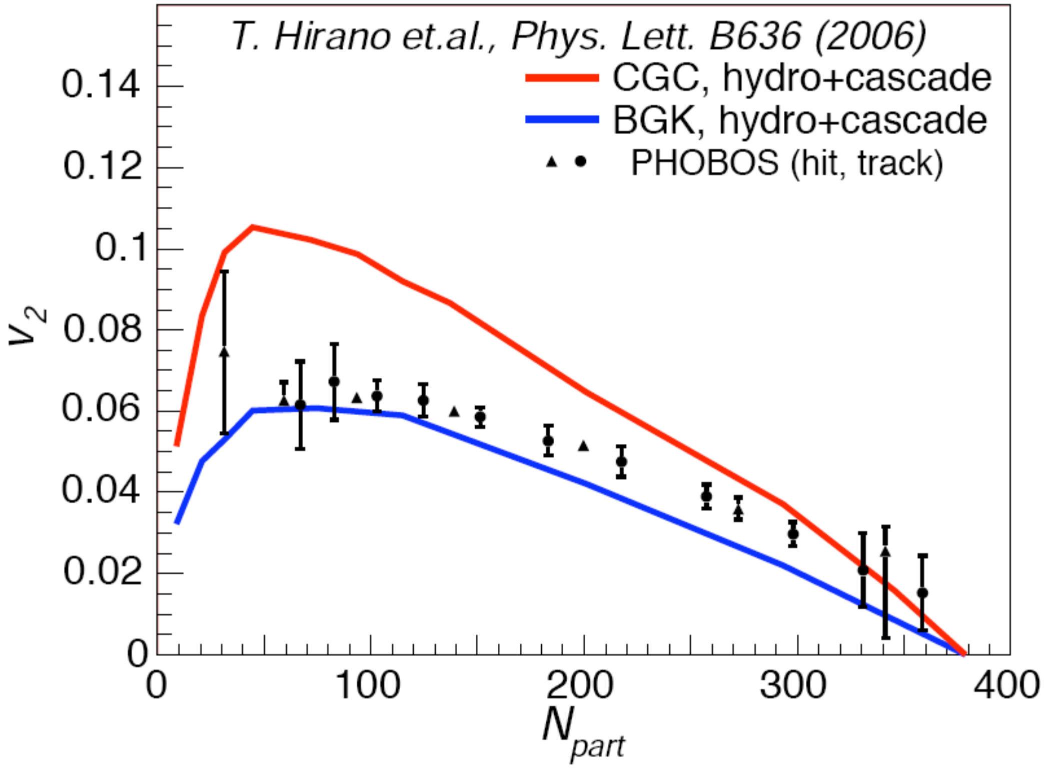
as the system expands are the correlations and fluctuations from the initial conditions carried over to the final state?



lumpy initial conditions:
NexSPheRio

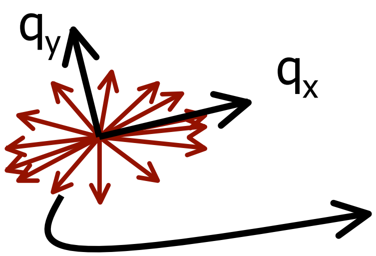


Understanding initial conditions



v_2 depends on initial deformation: fluctuations of v_2 can reveal information about fluctuations and correlations in the initial conditions

Flow vector distribution

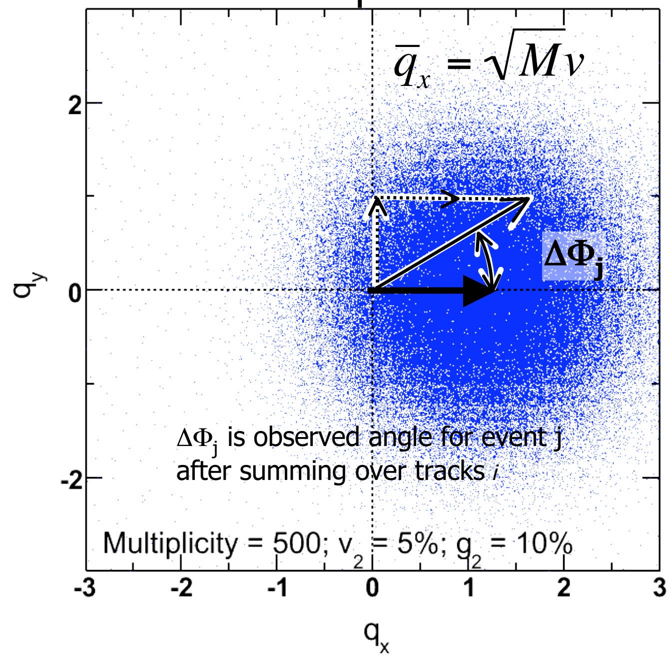


$$q_{n,x} = \frac{1}{\sqrt{M}} \sum_{i=1}^{M} \cos(n\varphi_i)$$

$$q_{n,y} = \frac{1}{\sqrt{M}} \sum_{i=1}^{M} \sin(n\varphi_i)$$

J.-Y. Ollitrault nucl-ex/9711003; A.M. Poskanzer and S.A. Voloshin nucl-ex/9805001

simulated q distribution



q-vector and v_2 related by definition: $v_2 = \langle\cos(2\varphi_i)\rangle = \langle q_{2,x}\rangle/\sqrt{M}$

width depends on

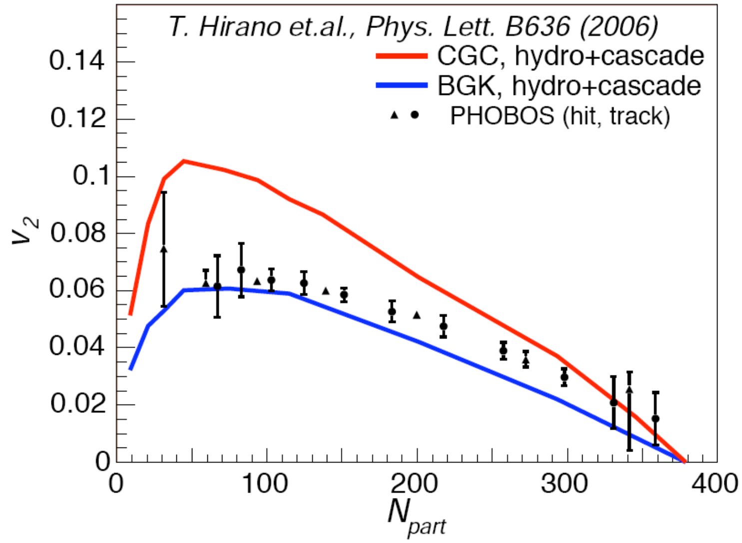
- non-flow: $\delta_n = \langle\cos(n(\varphi_i - \varphi_j))\rangle$ *(2-particle correlations)*
- v_2 fluctuations: σ_v

we measure dynamic width: $\sigma_{q,dyn}^2 = \delta + 2\sigma_v^2$

introduction

ambiguity arises in calculations from uncertainty in initial conditions

perfect fluid conclusion depends on ambiguous comparison to ideal hydro



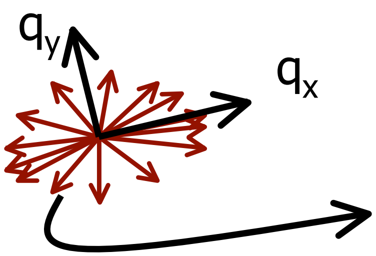
motivation to measure v_2 fluct.: find observable sensitive to initial conditions

Talk outline:

- analysis procedures and changes since QM06
- non-flow δ_2 and σ_{v2} from the q-distribution
- comparison to cumulants v{2}, v{4}
- v_2 of events with a “ridge” and/or a “jet”!

See STAR Poster: Navneet Kumar Pruthi

flow vector distribution



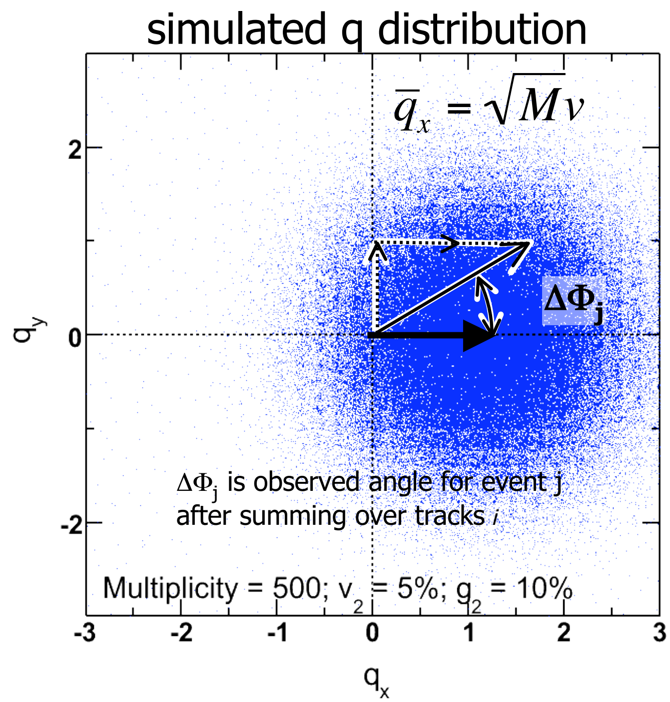
$$q_{n,x} = \frac{1}{\sqrt{M}} \sum_{i=1}^{M} \cos(n\varphi_i)$$

$$q_{n,y} = \frac{1}{\sqrt{M}} \sum_{i=1}^{M} \sin(n\varphi_i)$$

$$\sigma_{n,x}^2 = \frac{1}{2}(1 + v_{2n} - 2v_n^2 + M\delta_n)$$

$$\sigma_{n,y}^2 = \frac{1}{2}(1 - v_{2n} + M\delta_n)$$

J.-Y. Ollitrault nucl-ex/9711003; A.M. Poskanzer and S.A. Voloshin nucl-ex/9805001



q-vector and v_2 related by definition: $v_2 = \langle \cos(2\varphi_i) \rangle = \langle q_{2,x} \rangle / \sqrt{M}$

sum over particles is a random-walk ➔ central-limit-theorem

width depends on

- non-flow: ***broadens*** $\delta_n = \langle \cos(n(\varphi_i - \varphi_j)) \rangle$ *(2-particle corr. nonflow)*
- v_2 fluctuations: ***broadens***

flow vector distribution

from central limit theorem, q_2 distribution is a 2-D Gaussian

$$\frac{1}{q}\frac{dN}{dqd(\Delta\Phi)} = \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2}\left[\frac{\left(q\cos 2\Delta\Phi - \sqrt{M}\,v_2\right)^2}{\sigma_X^2} + \frac{q^2\sin^2 2\Delta\Phi}{\sigma_Y^2}\right]}$$

Ollitrault nucl-ex/9711003;
Poskanzer & Voloshin nucl-ex/9805001

$$\sigma_X^2 = \frac{1}{2}(1 + v_4 - 2v_2^2 + M\delta_2) \text{ and } \sigma_Y^2 = \frac{1}{2}(1 - v_4 + M\delta_2)$$

$$\delta_2 = \left\langle \cos 2(\varphi_1 - \varphi_2) \right\rangle_{nonflow}$$

x, y directions are unknown: ➔ integrate over all $\Delta\Phi$ and study the length of the flow vector $|q_2|$

$$\frac{1}{|q_2|}\frac{d\tilde{N}}{d|q_2|} = \frac{1}{|q_2|}\int_{-\infty}^{\infty} dv_2 \frac{dN}{d|q_2|} f\left(v_2 - \langle v_2\rangle, \sigma_{v2}\right)$$

fold v_2 distributions $f(v_2)$ with the q_2 distribution to account for fluctuations σ_{v2}

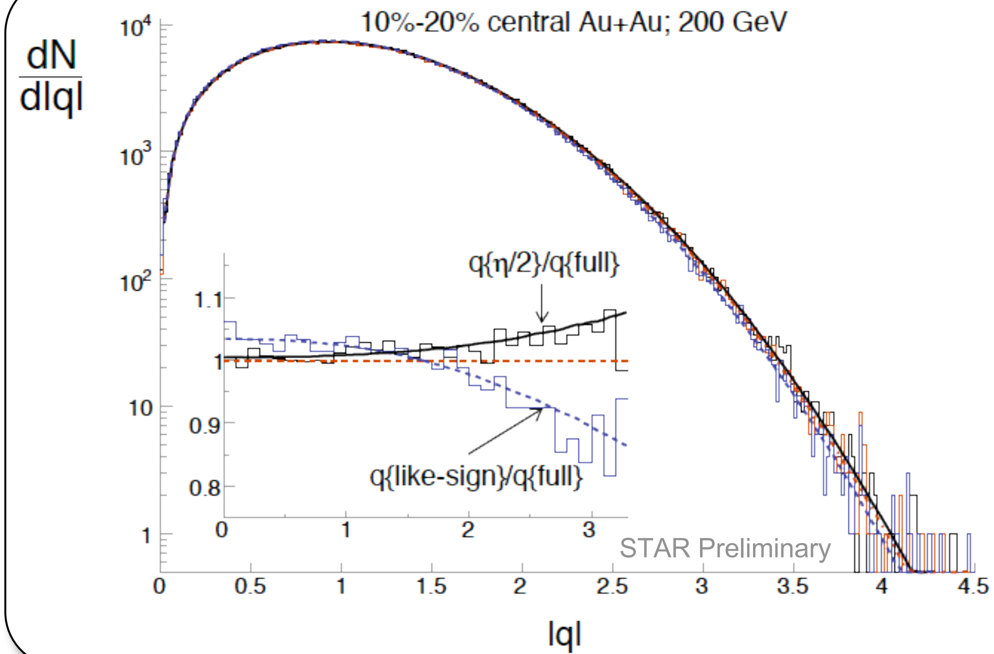
$$\sigma_q^2 \approx \frac{1}{2}\left(1 + M\left(\boxed{\delta_2 + 2\sigma_{v_2}^2}\right)\right)$$

difficult to distinguish non-flow from fluctuations (and vice-versa)

dynamic width dominated by non-flow and/or fluctuations ➔ not determined independently

$$\boxed{\sigma_{dyn}^2 \approx \delta_2 + 2\sigma_{v_2}^2}$$

correlations and the flow vector



width depends on the track sample

$$\sigma_q^2 \approx \frac{1}{2}\left(1 + M\left(\delta_2 + 2\sigma_{v_2}^2\right)\right)$$

differences are due to more or less non-flow in various samples

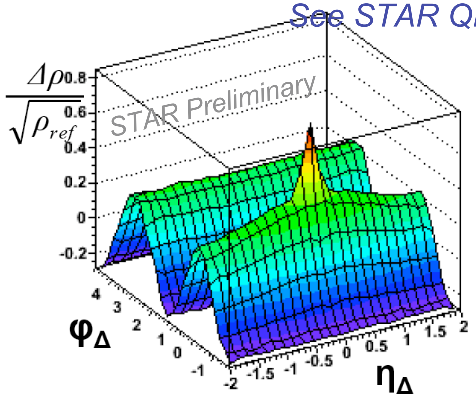
$$\delta_2 = \left\langle \cos 2(\varphi_1 - \varphi_2) \right\rangle_{correlated}$$

smaller δ_2 for like-sign (charge ordering)

larger δ_2 for small η (strong short range correlations)

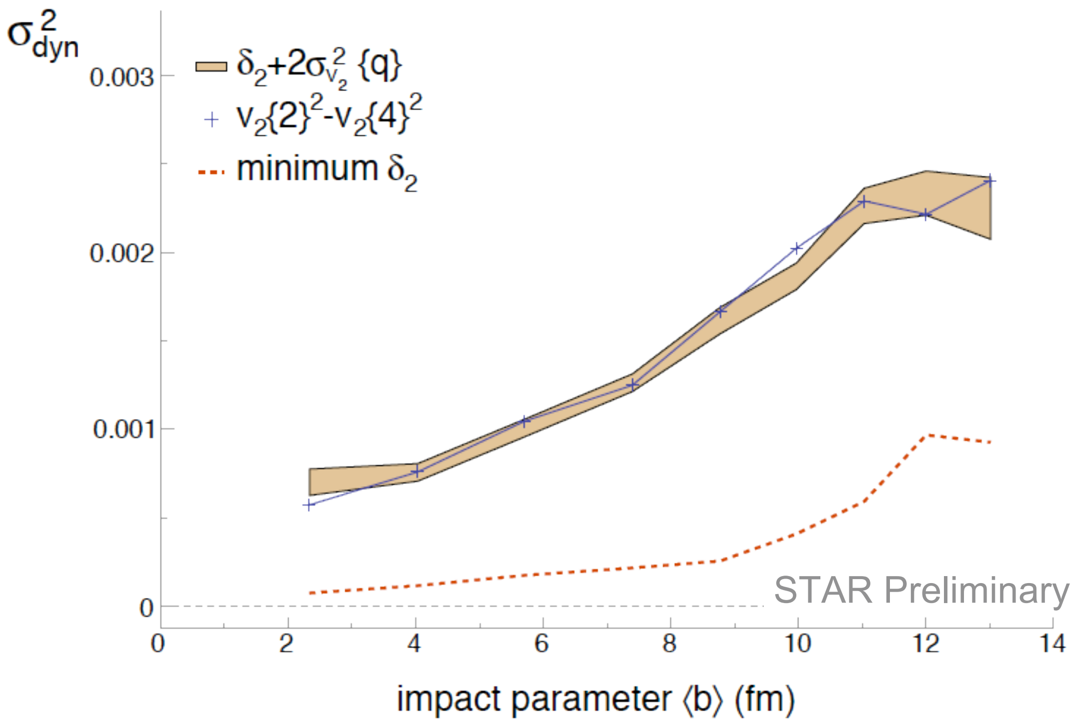
also in 2-D correlations: can be fit with a $\Delta\eta$ independent $\cos(2\Delta\varphi)$ term + non-flow structures

See STAR QM08 Talk: Michael Daugherity



N.B. relationship of measured δ_2 from 2 particle correlations and dynamic width is not trivial: depends on ZYAM and 2-component model (see backup slides)

dynamic width from dN/dq fit



the well constrained combinations of fit parameters are:

$$\langle v_2\rangle^2 + \sigma^2_{v_2} + \delta_2 = v_2\{2\}^2$$

$$\langle v_2\rangle^2 - \sigma^2_{v_2} = v_2\{4\}^2$$

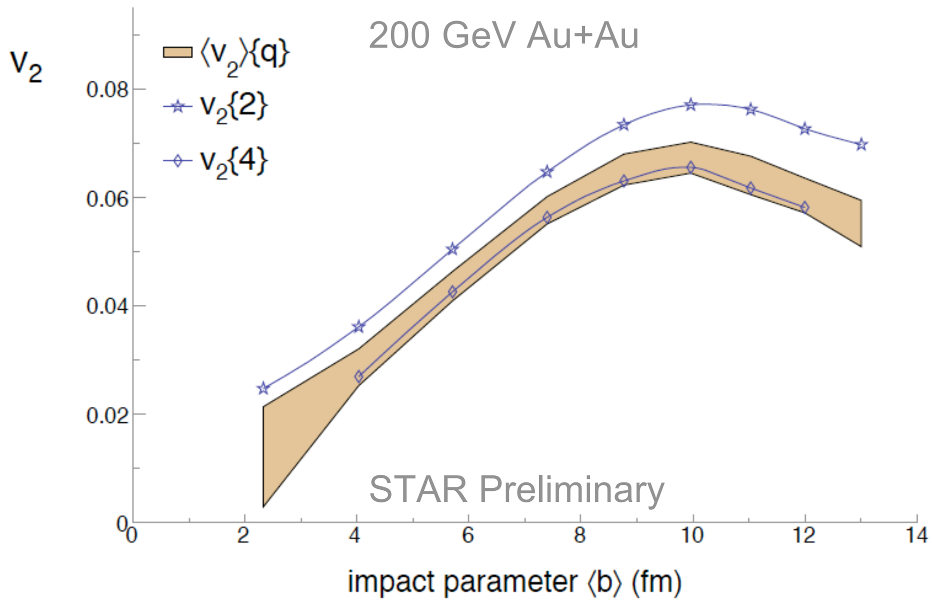
the dynamic width is the difference between the above equations

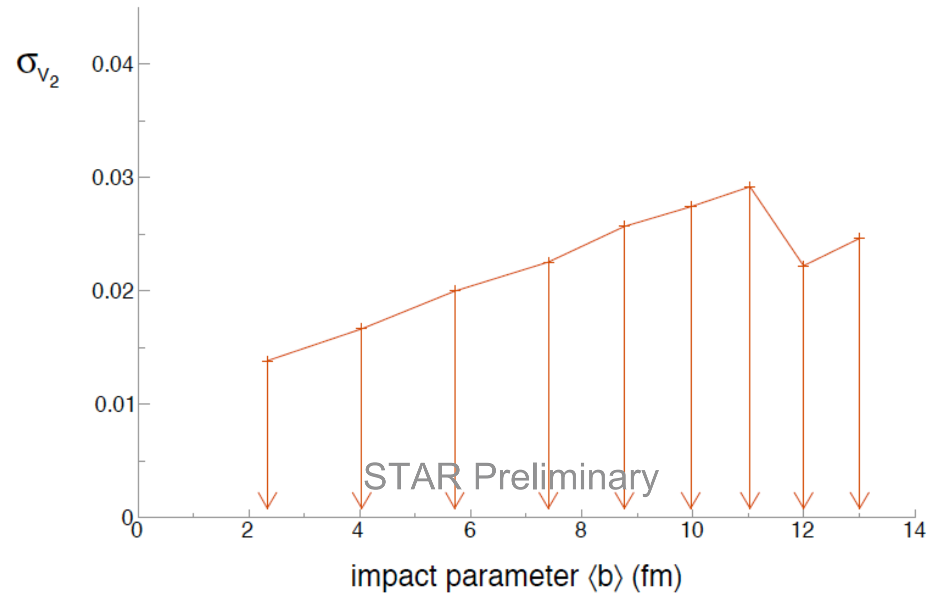
$$\sigma^2_{dyn} = \delta + 2\sigma^2_{v_2} = v_2\{2\}^2 - v_2\{4\}^4$$

see *Miller, Snellings, nucl-ex/0312008*

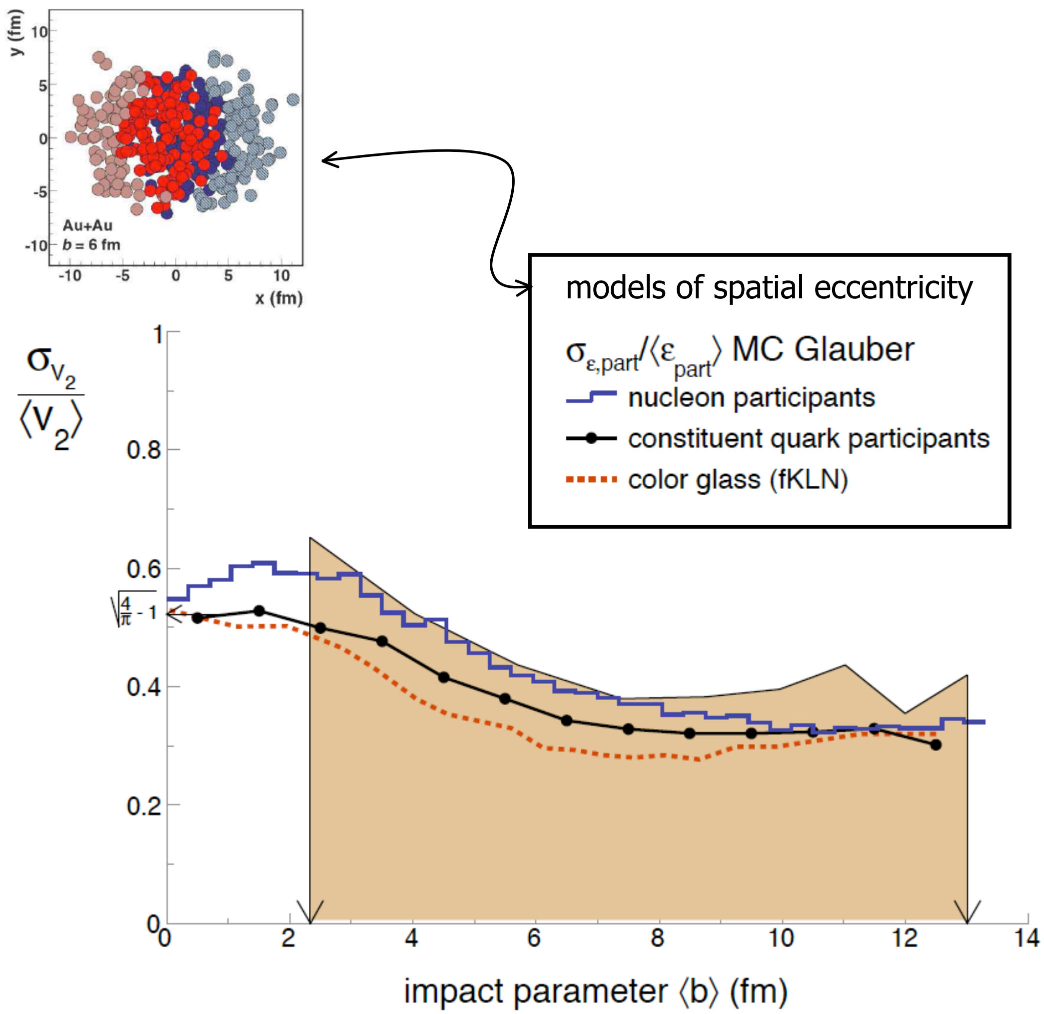
mean and width of $f(v_2)$

analysis places an upper limit on flow fluctuations





Comparison to models



confined quark MC:

treats confined constituent quarks as the participants

decreases eccentricity fluctuations

color glass MC:

includes effects of saturation

increases the mean eccentricity

comparison to hydro (NexSPheRio): *Hama et.al. arXiv:0711.4544*

eccentricity fluctuations from CGC: *Drescher, Nara. Phys.Rev.C76:041903,2007*

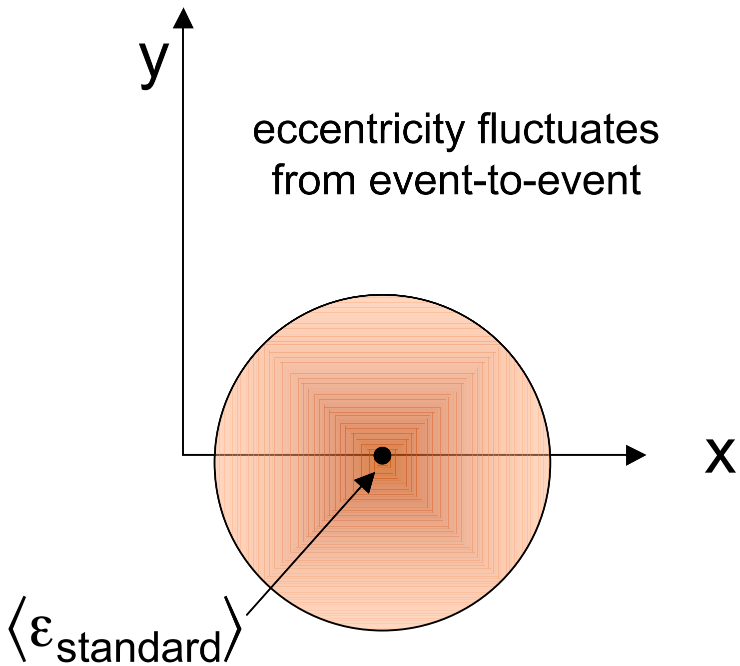
extraction of Knudsen number: *Vogel, Torrieri, Bleicher. nucl-th/0703031*

fluctuating initial conditions: *Broniowski, Bozek, Rybczynski. Phys.Rev.C76:054905,2007*

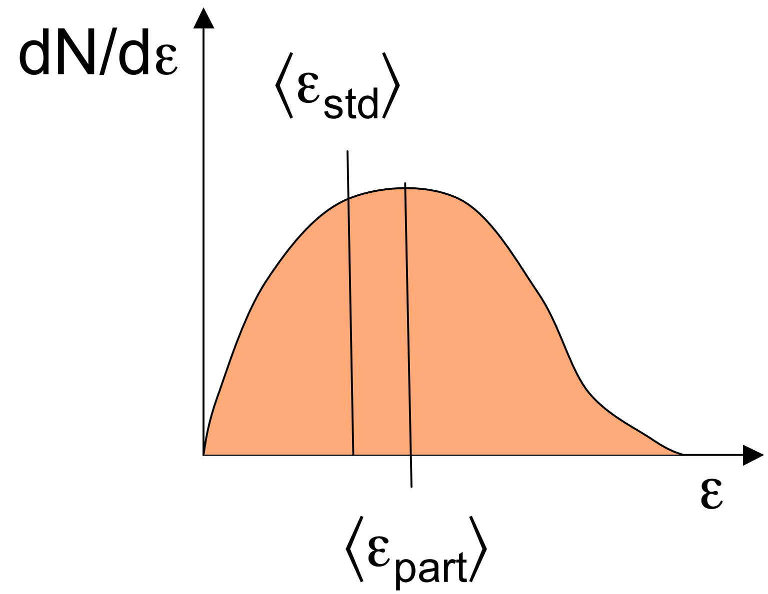
first disagreement with $\varepsilon_{standard}$ and use of quark MC: *Miller, Snellings. nucl-ex/0312008*

reaction- or participant-plane

reaction plane → rotation to major axis → defines the partipant plane



2-D Gaussian



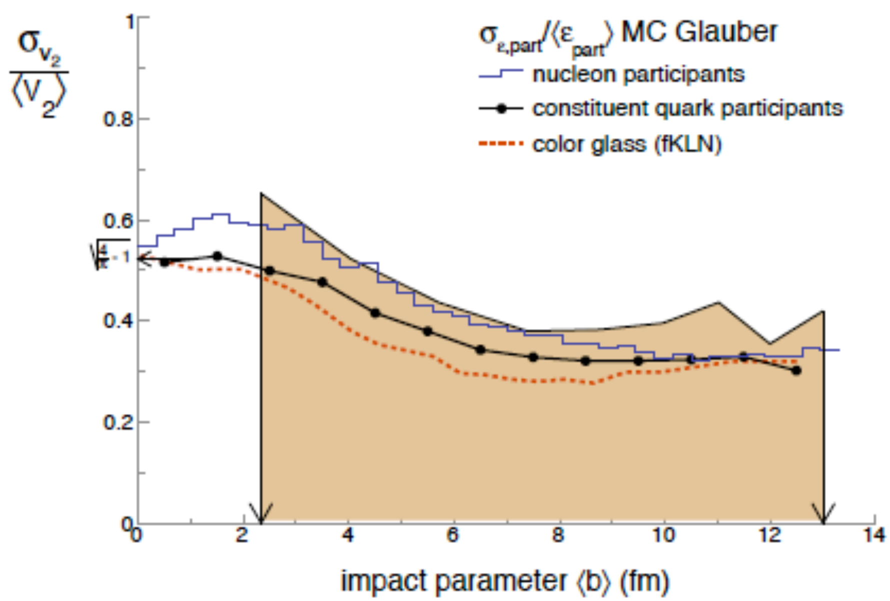
1-D Bessel-Gaussian

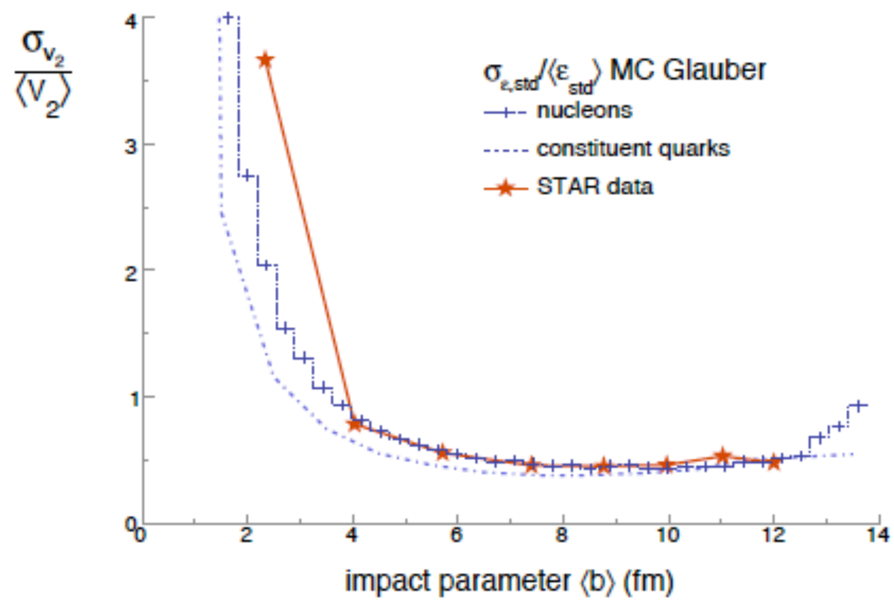
$I_0(\varepsilon_{part}\varepsilon_{std}/\sigma^2)\exp(-\varepsilon_{part}^2-\varepsilon_{std}^2/2\sigma^2))$

Fitting dN/dq with a Bessel-Gaussian allows for comparison to models of either the participant-plane or reaction-plane

Voloshin, Poskanzer, Tang, Wang: Phys.Lett.B:537-541

reaction-plane, participant-plane





- Data can also be presented in terms of the reaction-plane
- Assume Bessel-Gaussian shape for dN/dv_2
- use v_{std} instead of $\langle v_2 \rangle$
- Also gives good description: lesson is that initial geometric fluctuations dominate the dynamic width of dN/dq

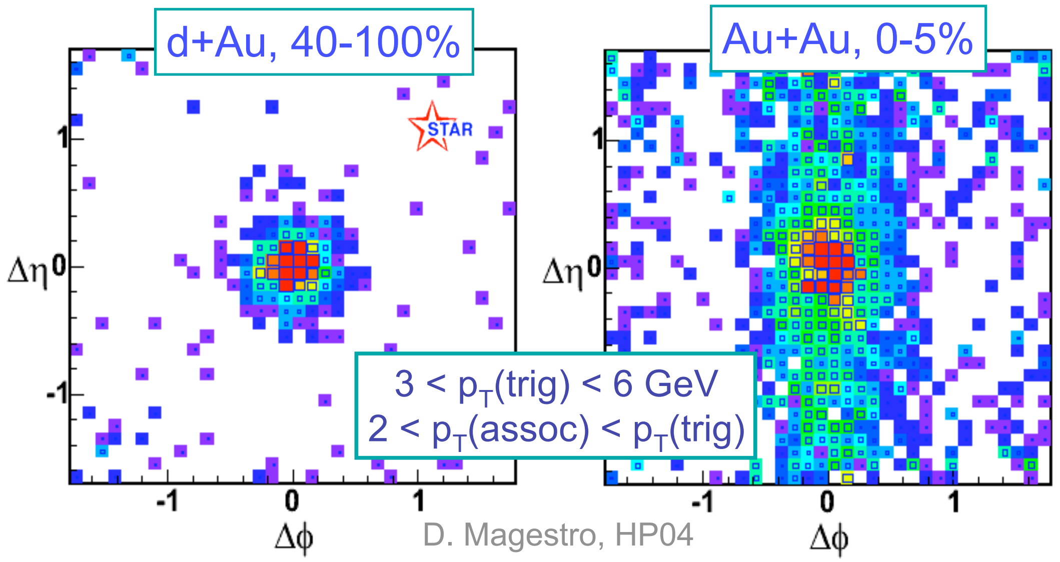
expected geometric fluctuations match observed v_2 fluctuations

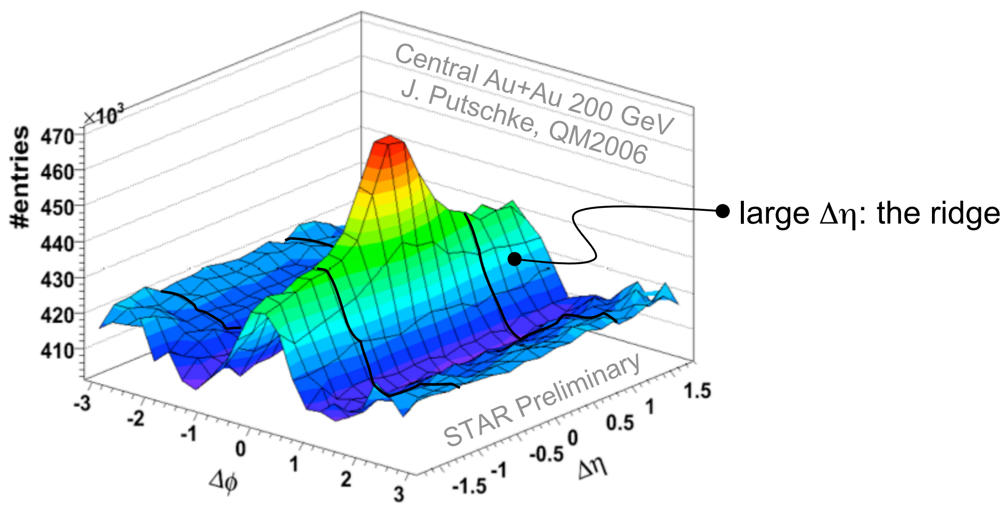
but what about two-particle correlations and non-flow?

don’t we see huge non-flow in 2-particle correlation data?

Long range correlations

structures unique to Au+Au collisions

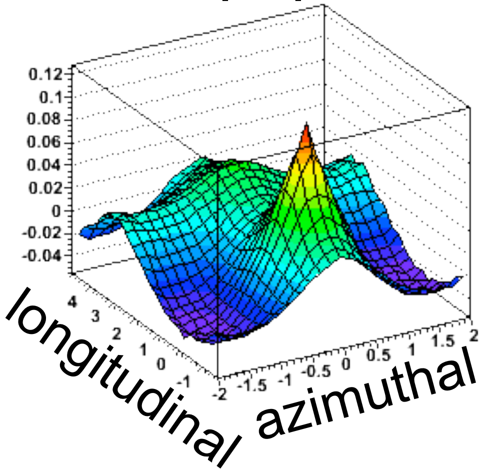


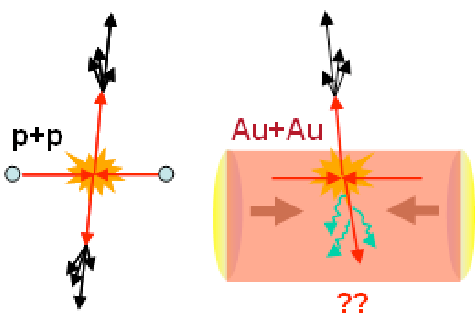


Two particle correlation densities

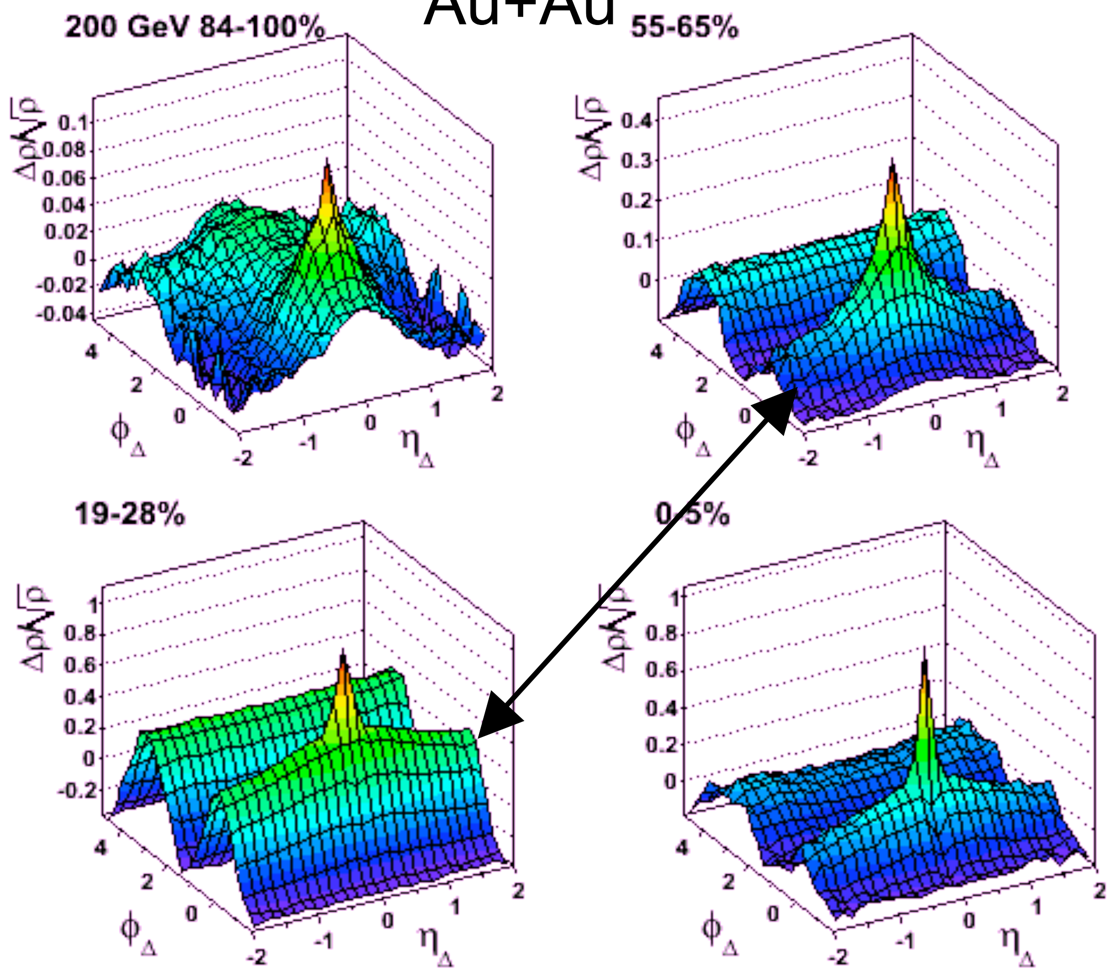
Correlations of all unique pairs of charged particles

p+p



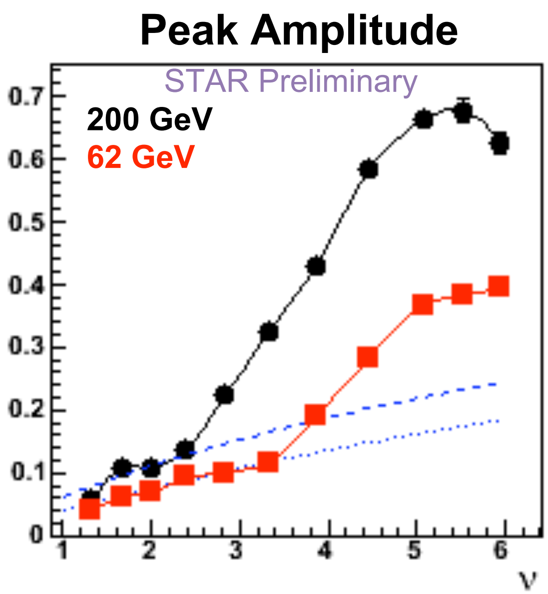


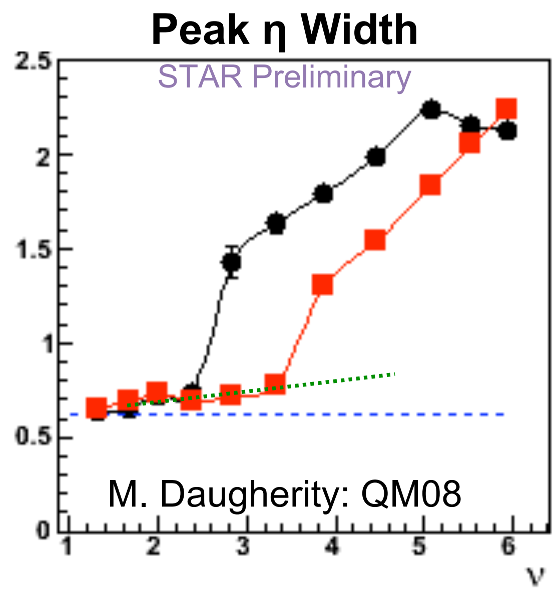
Au+Au

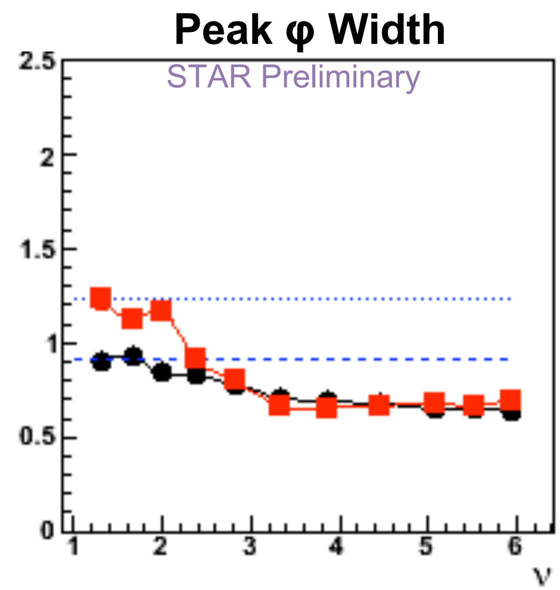


M. Daugherity: QM2008

Near-side peak







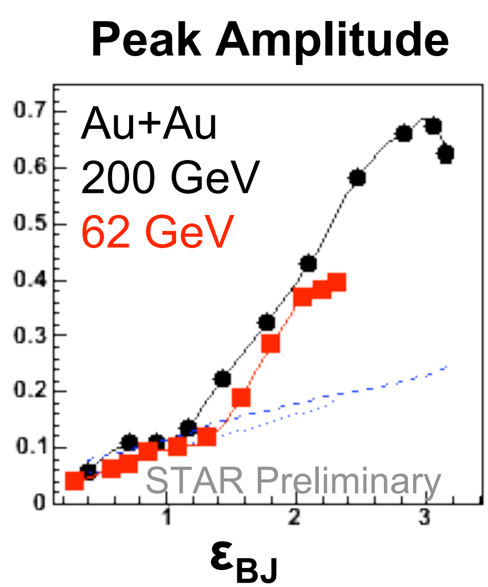
peripheral central

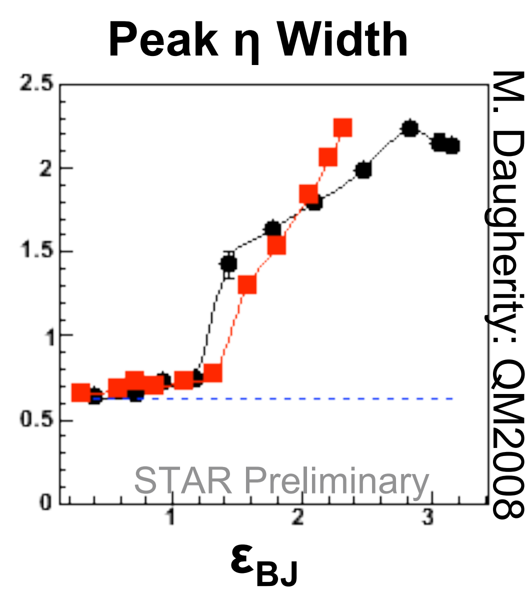
Large increase in peak amplitude and longitudinal width

Narrowing in azimuth (boost?)

Deviations between Au+Au and p+p scaling trends

Sudden jump in width and amplitude

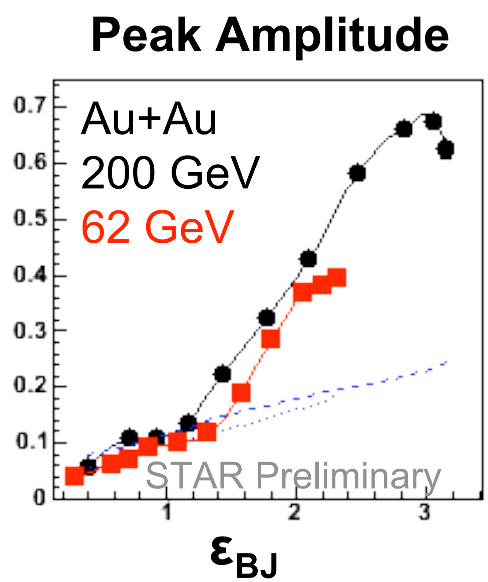


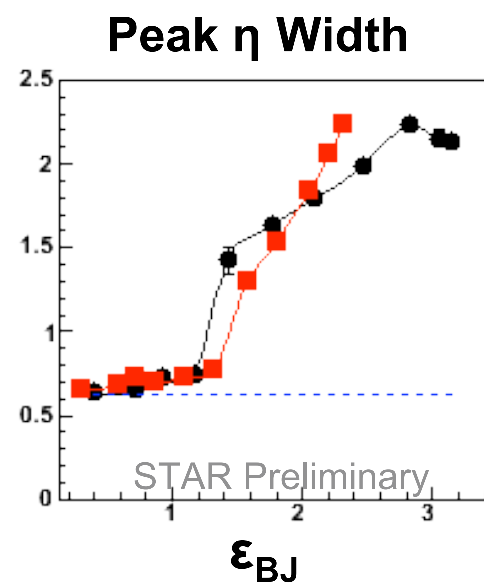


The abrupt transition occurs at the same energy density for two different collision energies!

$$\varepsilon_{BJ} = \frac{dE_T/dy\big|_{y=0}}{\pi R^2 \tau_0}$$

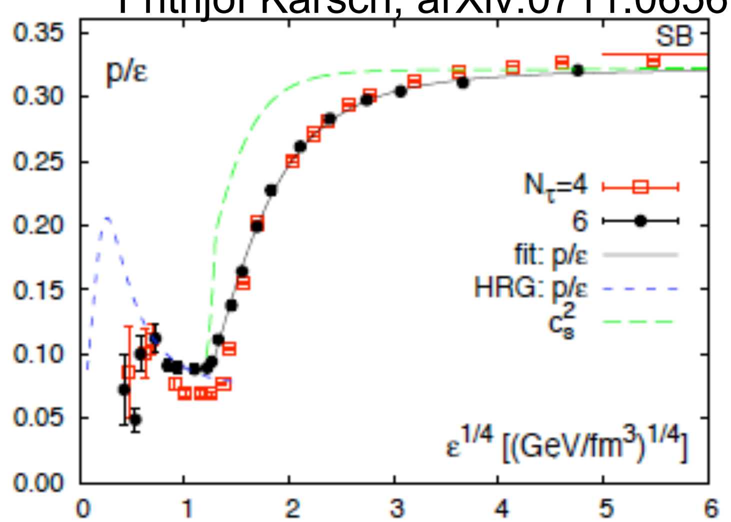
Sudden jump in width and amplitude





M. Daugherity: QM2008

Frithjof Karsch, arXiv:0711.0656



Liberation of colored degrees of freedom near ε = 1.5 GeV/fm^3?

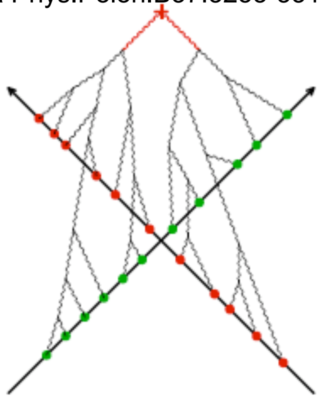
large pressure → QGP expansion?

initial spatial correlations translated to momentum space?

interesting checks: more energies, different size nuclei, and particle composition

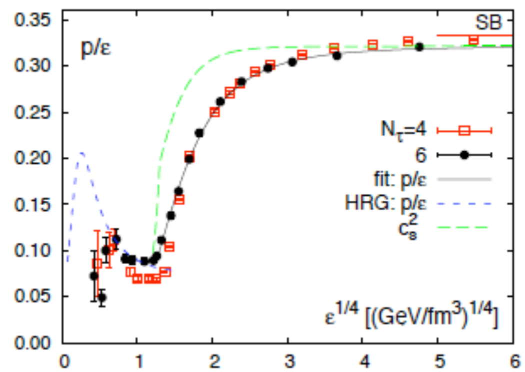
The Algebra

Venugopalan, Gelis
Acta Phys.Polon.B37:3253-3314,2006

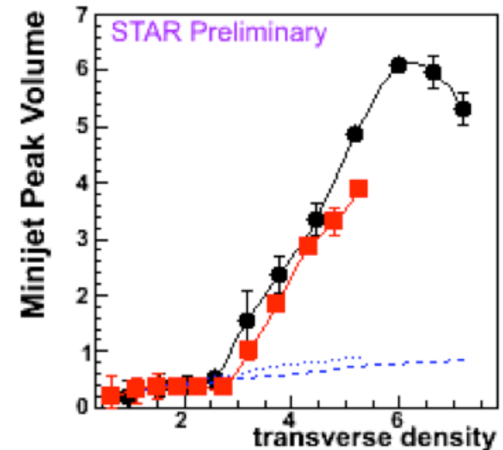


$\otimes$

Frithjof Karsch, arXiv:0711.0656



$\stackrel{?}{=}$



Initial State Fluctuations:

very general, seen in any model or calculation, EPOS, HIJING, Glauber, CGC

Quark Gluon Plasma Pressure:

first principles calculation of QCD finite temperature phenomena

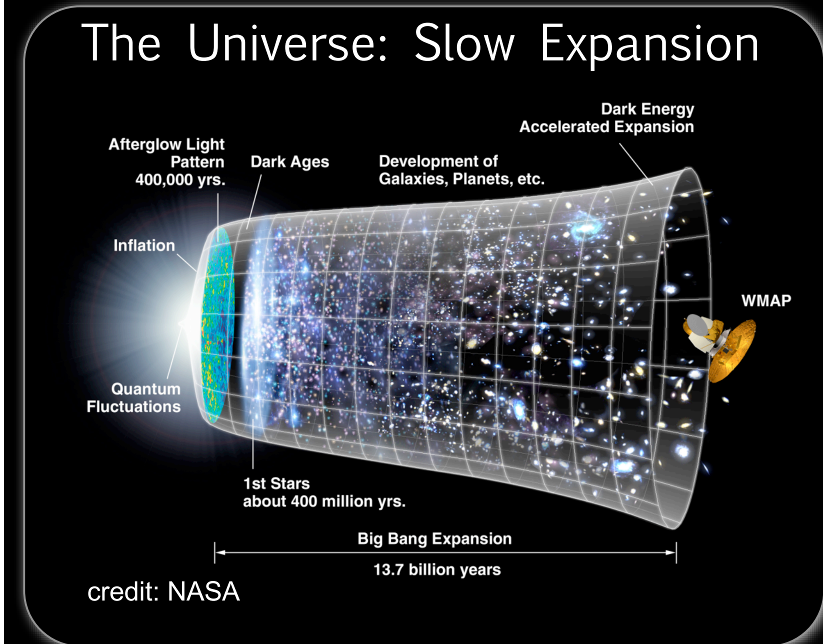
Large Long Range Small $\Delta\varphi$ Correlations

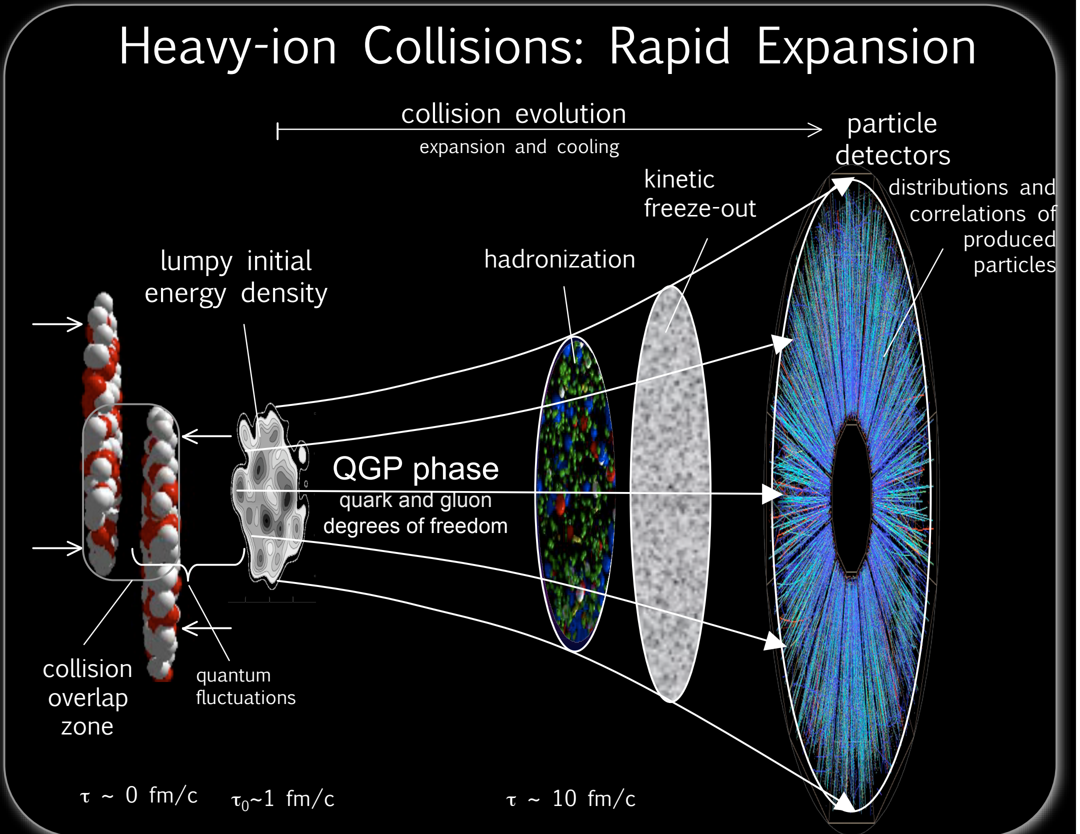
observed in heavy ion data

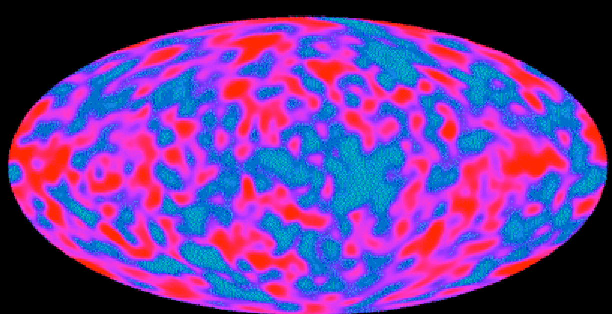
S. A. Voloshin, Phys. Lett. B **632**, 490 (2006); C. A. Pruneau, S. Gavin and S. A. Voloshin, Nucl. Phys. A **802**, 107 (2008); A. Dumitru, F. Gelis, L. McLerran and R. Venugopalan, arXiv:0804.3858 [hep-ph].

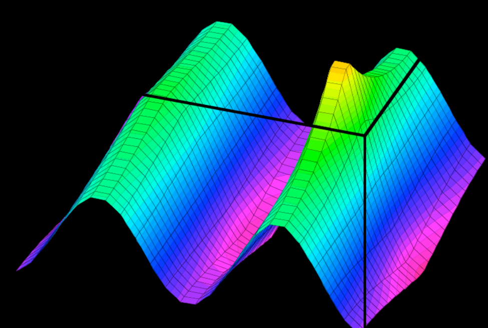
Here is the sensitivity to the EOS

Analogies with the early universe



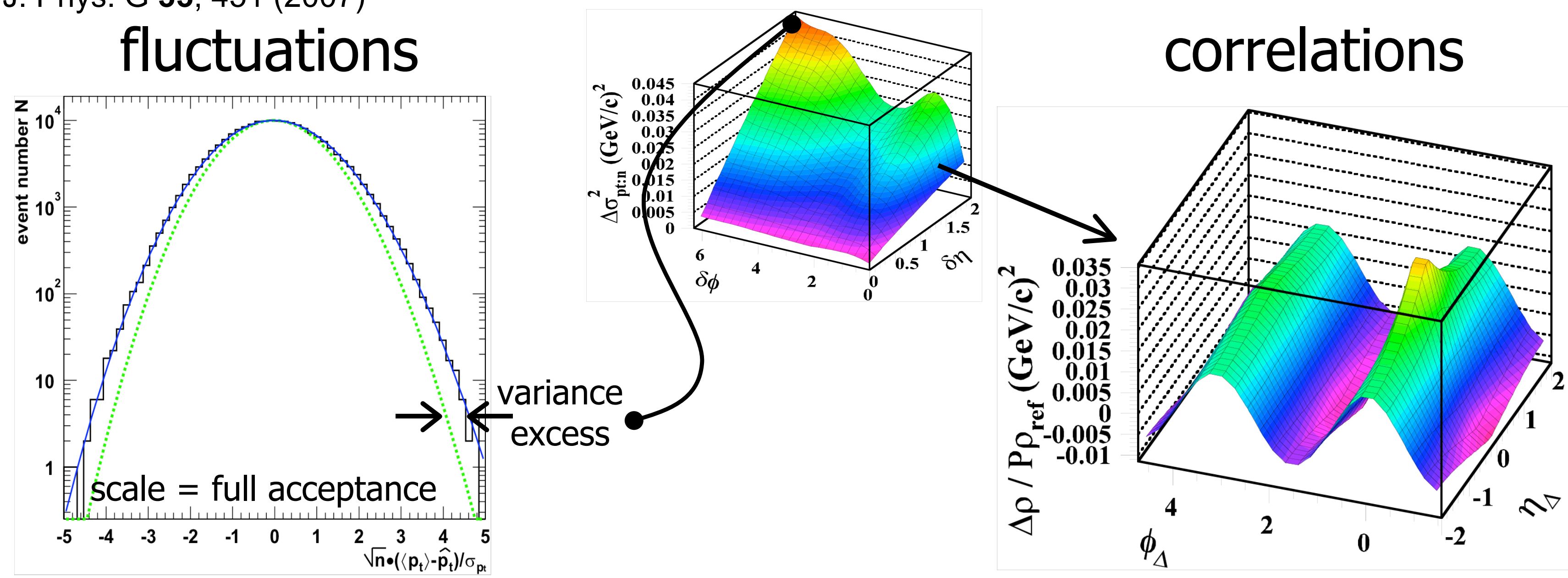






WMAP analogy: $\langle p_T \rangle$ fluctuations

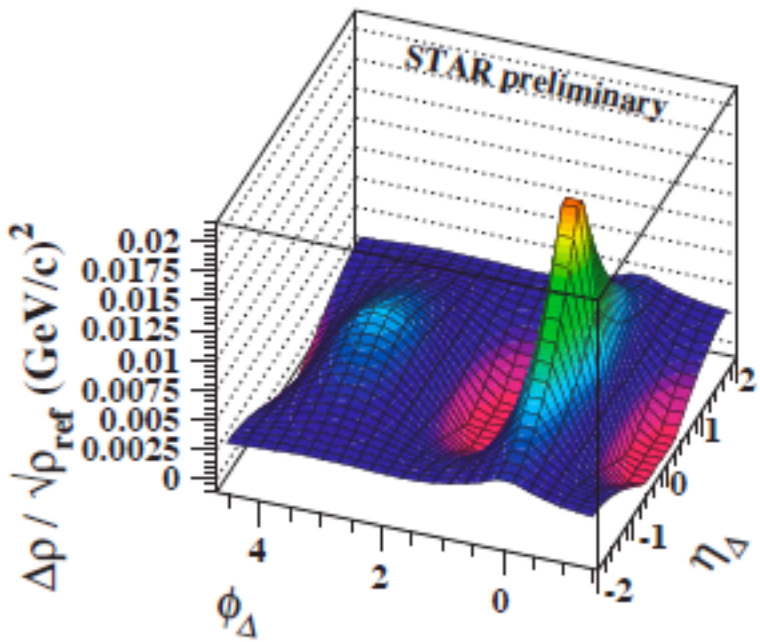
J. Adams *et al.* [STAR Collaboration],
J. Phys. G **33**, 451 (2007)



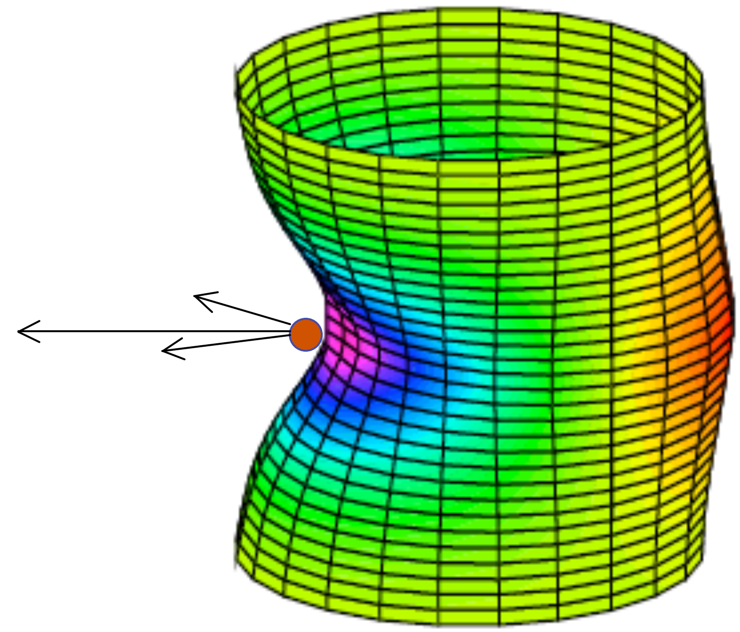
- scale dependence of $\langle p_T \rangle$ fluctuations tells us about p_T correlations
- $\langle p_T \rangle$ reflects the slope of the spectra; these measurements are the analogy to CMBR temperature fluctuations

The ridge and the valley

J. Adams *et al.* [STAR Collaboration],
J. Phys. G **32** (2006) L37



same data after subtraction:
cylindrical format

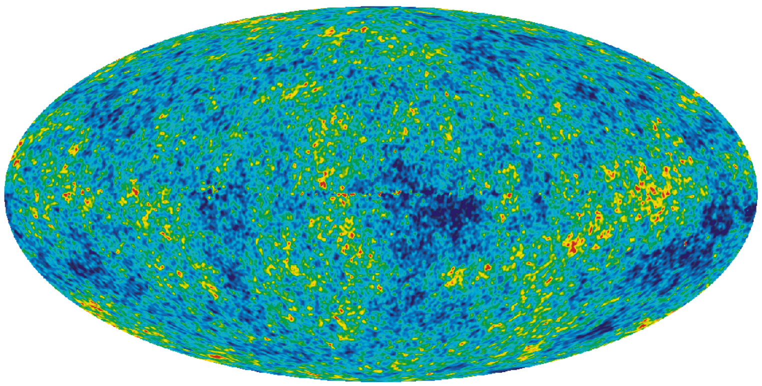


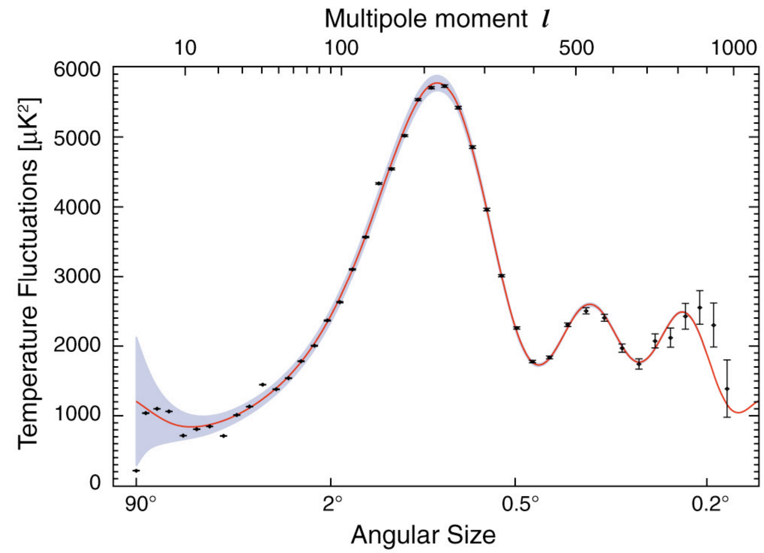
D. Prindle, QM05 (Poster)

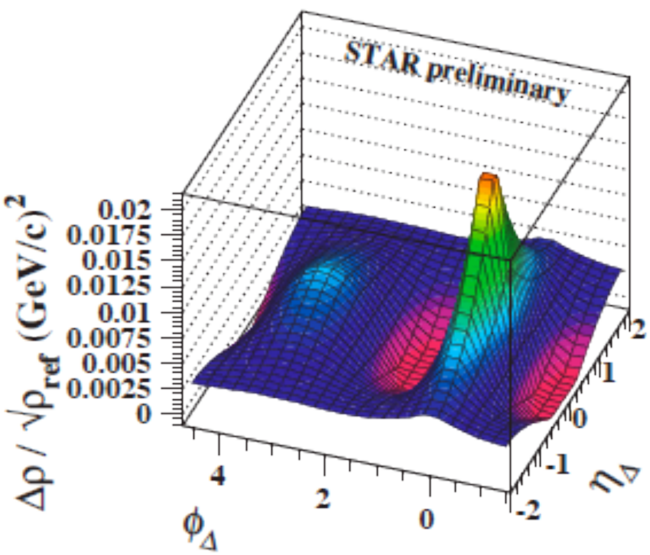
- subtract the elliptic modulation and near side peak
- anamolous depression apparent

One interpretation: medium response to an impinging minimum-bias jet?

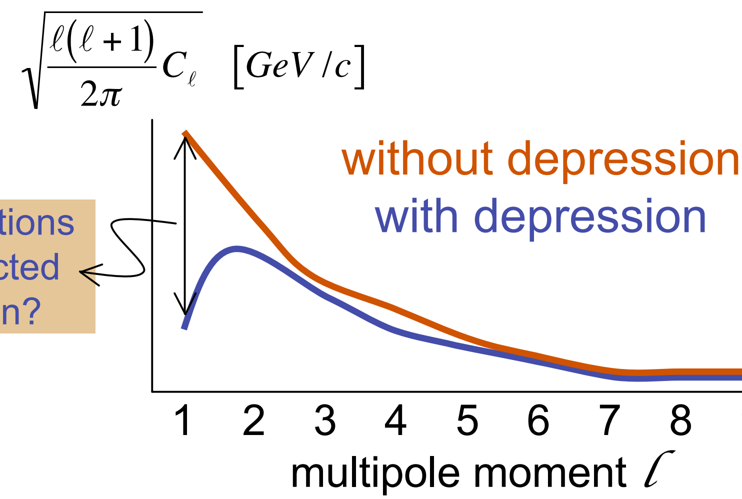
Multipole moments and the valley







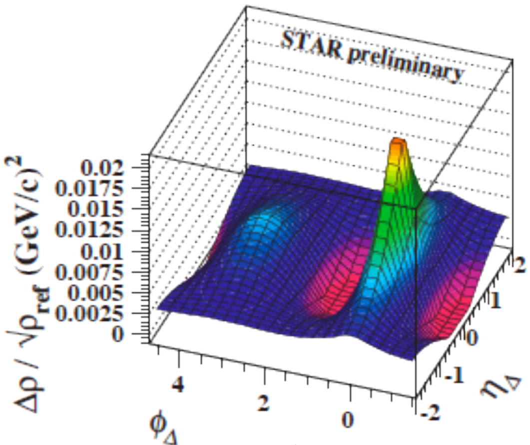
large scale fluctuations causally disconnected during the evolution?



See Also: Superhorizon fluctutions in HIC, Ananta P. Mishra, Ranjita K. Mohapatra, et al.

Harmonic decomposition

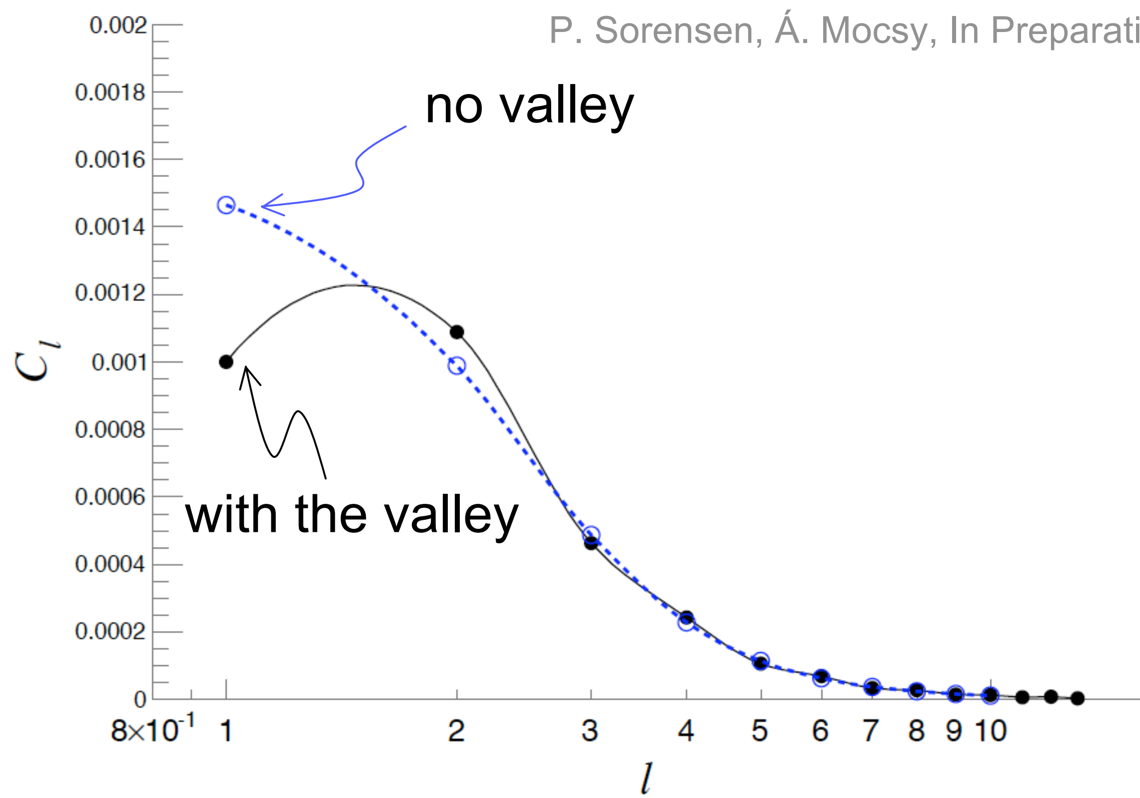
J. Adams *et al.* [STAR Collaboration],
J. Phys. G **32** (2006) L37



harmonic decomposition

Valley indicates suppression of lower multipole moments

model needed to generate a reference shape



Super-horizon fluctuations

fluctuations with large characteristic length scales remain super-horizon for a longer time

length scale

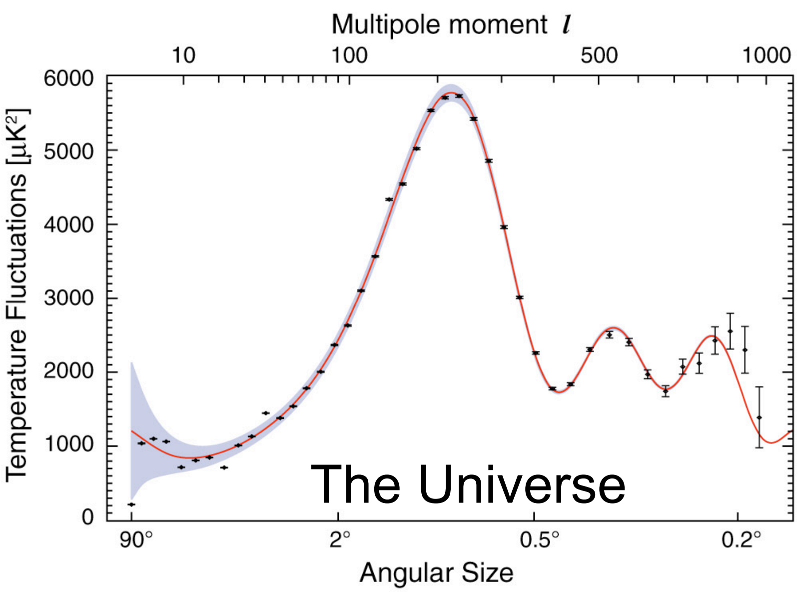
$$\lambda_\ell \approx \frac{R\{Au\}}{\ell}$$

causality and the finite lifetime ($\Delta\tau$) of the fireball prevents the largest modes from fully developing

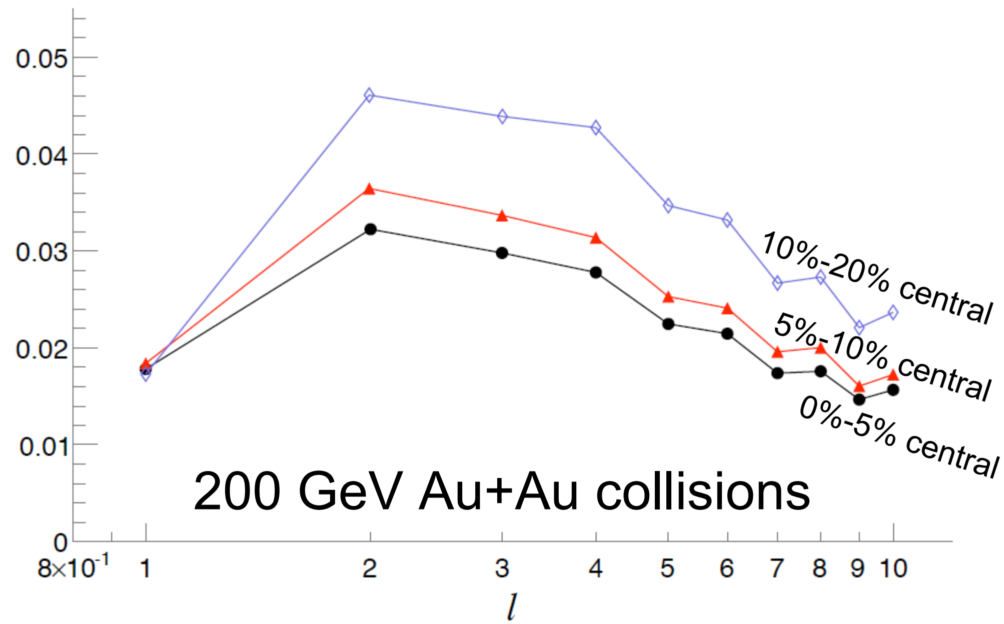
supressed modes

$$\lambda_\ell > c\Delta\tau$$

See Also: Superhorizon fluctutions in HIC,
Ananta P. Mishra, Ranjita K. Mohapatra, et al.



$\sqrt{\frac{\ell(\ell+1)}{2\pi}C_\ell}$ $[GeV/c]$ P. Sorensen, Á. Mocsy, In Preparation



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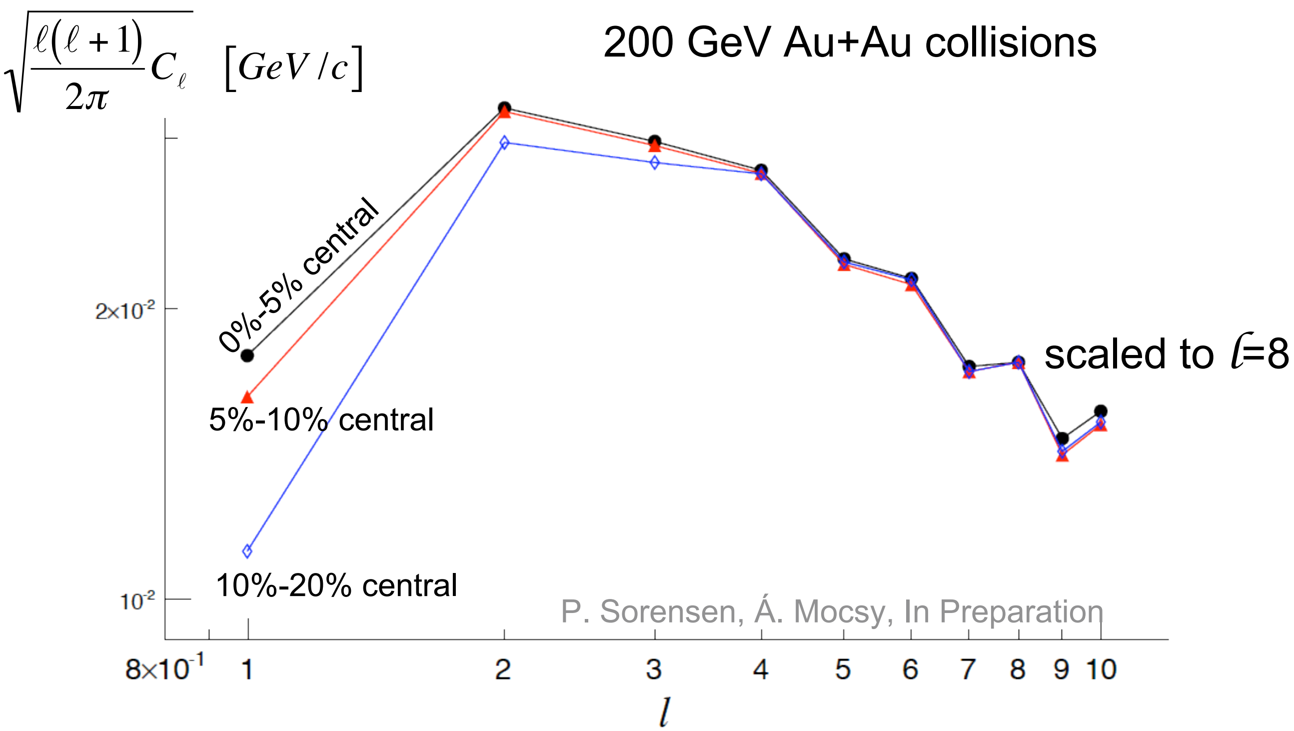
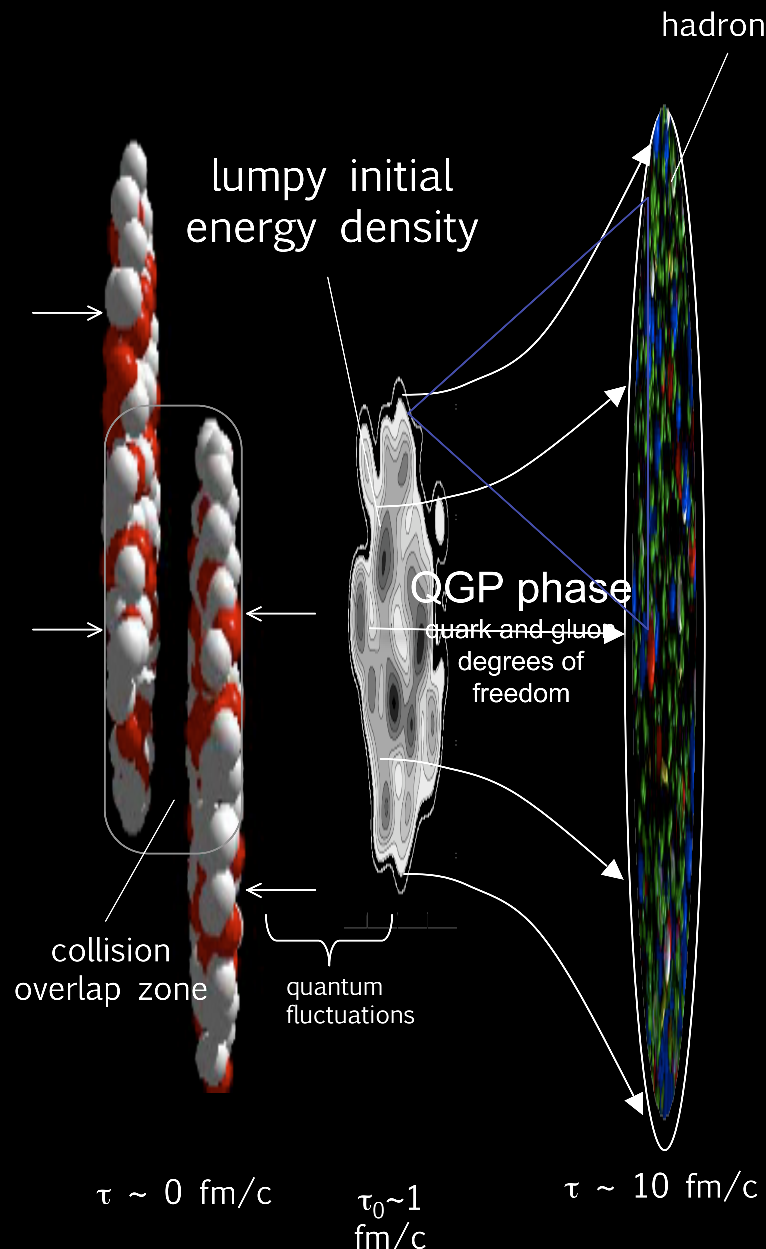


Life is short



Correct scale shows:

regions remain outside the event horizon

Conclusions

Dynamic width of dN/dq close to expected width from models of initial geometry fluctuations

Correlations show structures unique to A+A collisions

- a ridge: narrow in ϕ, broad in η
- ridge develops suddenly near ε=1.5 GeV/fm^3
- features of $\langle p_T \rangle$ fluctuations are consistent with super-horizon fluctuations from the initial conditions

If geometry fluctuations are real: near-side "minijet" peak must come from those, not fragmentation

Do trends indicate sudden turn on of color degrees-of-freedom?

Future tests:

vary beam energy (2010!)
vary system size
add particle identification
correlate trends with other probes (J/ψ suppression etc.)